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By J. S. Plaskett, F. R. S.

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Over twenty-five years ago, Hartmann first observed in the spectroscopic binary δ Orionis that the *H* and *K* lines of calcium did not share in the velocity oscillations, due to the binary motion, of the hydrogen and helium lines of the star, but remained relatively fixed in position. Hence the name "stationary" calcium lines which has served for their designation almost to the present time. Although many more examples of spectroscopic binaries which were always of early type, of very high temperature stars with stationary calcium lines were discovered in the following twenty years, it was believed that these lines were associated only with binaries and were due to the absorption of a surrounding cloud of ionized calcium attached to and moving with the binary system in its journey through space.

I was first led to suspect that this was not the true explanation when the investigation of the massive eclipsing system *Y* Cygni in 1920 showed that the constant velocity given by the "stationary" lines in this star differed by nearly 40 km. per second from the velocity of the centre of gravity of the revolving pair. In such a case of rapid relative motion the pair would soon escape from any limited surrounding cloud. This was only an isolated example but when it was shown about three years later in my investigation of the radial velocity of stars of type *O*, that a similar phenomenon was repeated in these stars, it seemed necessary to modify the early hypothesis. The stars of *O* type are the stars of highest temperature, greatest mass and highest luminosity in the sky and it was soon found that these "stationary" lines were present not only in spectroscopic binaries but in practically all stars of the class and that the velocity given by these lines generally differed, frequently markedly, from the velocity given by the lines of hydrogen, helium, etc. arising in the stellar atmosphere itself. These differences were sometimes so great, up to 50 and 60 km. per second, in comparison to the probable errors, of the order of one km. per second, of the velocities as to leave no reasonable doubt of the presence in space of gaseous matter containing ionized calcium through which these *O* type stars were rushing about in all directions.

The wide distribution of this gaseous material was more evident, and its independence of ordinary stellar matter and the spectral lines produced by this matter, was rendered more certain by the appearance of these "interstellar" lines, as we prefer to call them, in the spectra of the novae and of the Wolf Rayet stars in which no ordinary star lines appear. Further, when it was shown that this "interstellar" matter was nearly stationary with respect to the stellar system the conclusion was almost inevitable that it had a relatively extensive distribution, and that the stars were moving rapidly in all directions through it. As these "interstellar" calcium lines, differentiated from the other star lines by their extreme narrowness and sharpness, had not hitherto appeared in stars of type later than B3, in stars of the highest temperature only, it was assumed that the calcium in this diffuse matter was ionized and rendered absorbing at *H* and *K* by the excitation of neighboring high temperature *O* and *B* type stars.

This hypothesis, following closely Hubble's ideas of the excitation of the luminous gaseous nebulae by neighboring high temperature stars, was due mainly to the suggestion of my son, H. H. Plaskett, now professor of astrophysics at Harvard and required the assumption of a much wider distribution of this diffuse matter than was entailed by the earlier hypothesis of a surrounding cloud of material. Further, as the *D* lines of neutral sodium, of the same sharpness and stationary position as *H* and *K*, had also been found in these high temperature stars, there seemed good reason to believe that the interstellar matter was of the same composition as the stars and contained most of the elements present on the earth. The *D* lines and *H* and *K* are however the only lines likely to be present in the readily observable region of stellar spectra as the ultimate lines of other elements of sufficiently great abundance are mostly in the far ultra-violet. There finally resulted the hypothesis, advanced about 1923, that there was an extensive distribution of very diffuse matter practically stationary with respect to the stellar system extending to distances of several thousand light years, through which the stars were moving rapidly in all directions and which was rendered absorbing to the *D* lines and to *H* and *K* by the excitation of the stars of highest temperature.

I have been led to believe that the results of this investigation, demonstrating the rapid motions of the hottest and most distant stars in the sky in all directions through relatively stationary diffuse matter in interstellar space formed the starting point for Eddington's masterly exposition of the physical conditions of this diffuse matter

as given in the 1926 Bakerian Lecture of the Royal Society. If so, it is a striking instance of a deduction of great cosmic importance following closely upon accurate observational data obtained for an entirely different purpose. I am proud of having provided the observational material and given a preliminary hypothesis on which this important contribution of Eddington's may have been based and would like to believe that other work of ours may prove equally useful. While it is natural for an astronomer to wish to discuss as fully as possible his own observations, I think he should realize, particularly if he is fortunate enough to have the observational opportunities of a 72-inch telescope, that it will be generally more useful to science if he devotes his energies mainly to making accurate observations. In this particular case, however, as will be seen in the sequel, we were fortunate enough not only to provide the starting point of a great contribution, but to furnish recently the additional data which rounded off and gave the final finishing touch to Eddington's theory.

In his Bakerian Lecture, Eddington discussed theoretically the physical condition present in interstellar space and, on the *assumption* that the diffuse matter was uniformly distributed except where local condensations formed the diffuse nebulae, showed that the density of this matter could not be greater than about 10^{-24} gm/cm^3. Otherwise the gravitational force due to the combined mass of this diffuse matter and of the stars would give velocities to the latter considerably greater than observed. Some three years later Gerasimovic and Struve from calculations based on the intensity of the "interstellar" line K gave a density of about 10^{-26} gm/cm^3 only one hundredth of Eddington's admittedly maximum value. It will probably be of interest, before proceeding to give some idea in more familiar terms of what a density of 10^{-25} gm/cm^3, the mean of the two estimates, actually means. Obviously it implies that one gram of this diffuse matter will be distributed through a volume of space 10^{25} c.cm., a cube with sides 2×10^8 cm., or about 1400 miles. Or in the whole volume of the earth, there would only be about 4 ounces of this material. In the face of this almost inconceivable tenuity the highest terrestrial vacuum is crowded with molecules.

Eddington's calculations of the temperature were equally interesting although almost paradoxical in character. The temperature of such diffuse gaseous matter calculated as of the order of 10,000° or 12,000° C., is defined as the speed of the molecules given by such a temperature

and not as the temperature, some 270° C. below zero that a black body in outer space would assume. This molecular speed or temperature is due to and was calculated from the radiation from all the stars and is so high that most of the calcium present will be doubly ionized and the sodium singly ionized, these two elements being the only ones likely to give lines of sufficient intensity in the observable region of stellar spectra. Both of these ionized atoms however give their fundamental lines only in the far ultra violet, where they cannot be observed. However, about one part in 3000 of the calcium atoms would be singly ionized and thus capable of absorbing star light at *H* and *K* but only one part in 2,000,000 of the sodium atoms would remain neutral. Eddington calculated at the density of 10^{-24} gm/cm^3 that there should be sufficient absorption to show the *H* and *K* lines in stars at a distance of about 100 parsecs, 325 light years. There now seems good reason to believe that these interstellar lines do not become plainly visible in stars nearer than two or three times that distance, an indication of a lower density of the diffuse matter. Similarly, according to theory there will be so small a fraction of neutral sodium left that the *D* lines should never be visible, whereas observation shows they are of practically the same intensity as *H* and *K*. So much the worse then for the theory in which some unknown factor must enter. Gerasimovič and Struve calculate the effective temperature as nearer 15,000° which makes the presence of the *D* lines all the more mysterious.

We may now with advantage summarize briefly what has been learned about this very diffuse matter in interstellar space. The investigation of the *O* type stars had shown that this matter was widely distributed through the stellar system and that the high temperature stars were moving rapidly through it in all directions. It was further shown that after the removal of the solar motion, the residual velocities were relatively small and that this diffuse matter, which was later assumed to be uniformly distributed throughout the stellar system was nearly at rest with respect to this system. Eddington had calculated in a beautifully complete way its physical properties and it appears that the density is of the order of 10^{-25} gm/cm^3, four ounces in the volume of the earth, and that the temperature as represented by the molecular speed is from 10,000° to 15,000° C. As a consequence of the assumption of uniform distribution, the greater the distance of the star, the greater the depth of absorbing matter and the stronger will be the *H* and *K* lines. The *D* lines will

behave similarly, but, owing to the greater difficulty of observing the latter, the data are practically confined to *H* and *K*.

Struve early recognized that, if this interstellar matter were uniformly distributed, the strength of *H* and *K* should increase with the distance of the star. His examination of slit spectrograms of *O* and *B* type stars at Yerkes, Victoria, Lick and Mt. Wilson observatories gave somewhat conflicting results but a second attempt from the great wealth of Harvard objective prism spectra showed a gradual increase of intensity of the *K* line as the stars became fainter and hence presumably more distant. There was, however, owing to heterogeneity of the material some uncertainty about his conclusions, and a later investigation by Gerasimovič and Struve on the motions of this interstellar matter, a considerable part of their observational material consisting of published Victoria results was of a qualitative rather than a quantitative character. I think it is preferable therefore to give here the results of the observational work at Victoria, purposely withheld until the data were complete and definite quantitative results were available.

The earlier Victoria results proved that the high temperature stars were moving in all directions through diffuse gaseous matter, shown to be approximately at rest with respect to the stellar system. Eddington then calculated, in his masterly Bakerian lecture, the physical conditions of this interstellar material on the assumption that it was uniformly distributed throughout the stellar system. The recent Victoria results by my colleague, J. A. Pearce, and myself have not only definitely established the uniform distribution of the diffuse matter but shown that it is not exactly at rest as earlier supposed but partakes in a beautifully exact way of the differential motions produced by the rotation of the galactic system.

The observational material on which these final results are based has been gradually accumulating at Victoria for nearly ten years, first in my own work on the radial velocities of the *O* type stars and since 1924 in our joint investigation of the radial velocities of all *B*0 to *B*5 stars brighter than 7.5 visual magnitude and north of declination $-11°$ whose velocities had not been previously determined. Altogether over 500 *O* to *B*5 stars were critically examined for the presence of "interstellar" *H* and *K* and a catalogue compiled. This catalogue contained over 260 stars, all but about a dozen of which were obtained at Victoria, and in which the radial velocities of the interstellar matter between us and the corresponding stars were determined. For

about a dozen, such as the Novae and Wolf Rayet stars, no stellar velocity can be obtained while in about 20 others with reliable interstellar velocities, the stellar velocity was uncertain. Hence there were for the discussion 230 stars in which not only the radial velocity of the star itself but the velocity of the diffuse matter between us and the star was known and for which an estimate of the intensity of the "interstellar" *H* and *K* lines was available.

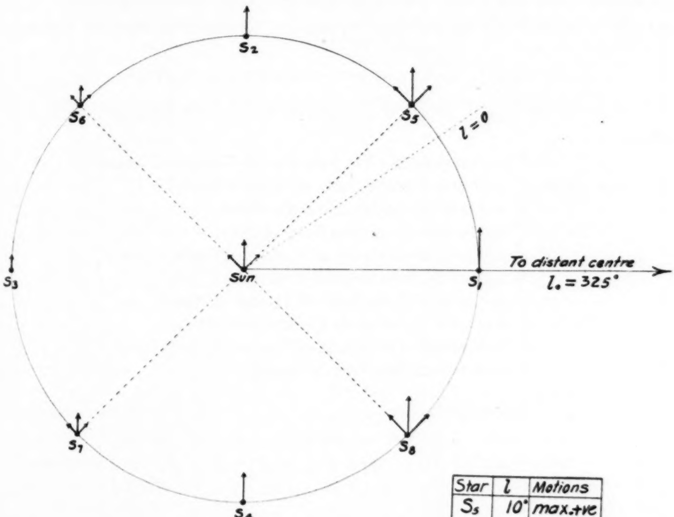
It will be remembered that the early work on the *O* type stars had shown that the radial velocities of the intervening diffuse matter, after the removal of the component of the standard solar motion of 20 km. per sec. towards $\alpha = 271°$, $\delta = +28°$, the residual velocities, as they are called, were relatively small, as if the diffuse matter was practically at rest with respect to the stellar system, with the stars moving through it in all directions. The final analysis of all the 260 residual motions shows however that the interstellar matter is not exactly at rest but partakes, along with the stars, in an orderly and majestic rotation of the galactic system. I think I may safely assume that everyone in my audience has heard something about the galactic rotation based on the work of Lindblad and Oort and most convincingly demonstrated from the motions of the *O* and *B* type stars obtained at Victoria. Possibly, however, a short description of the essentials of the rotational idea may be useful.

It would seem at first sight an impossible task to determine, from our position within the stellar system, where all the stars we can observe are rotating as well as ourselves, and when the galaxy can not be observed from without, whether any such rotation exists. If the stars and other matter throughout the system are uniformly distributed, elementary dynamics at once indicates that all the stars will revolve with the same angular velocity or the system will rotate like a solid disc or wheel. In such a case there will be no relative motion between the sun and neighboring stars and no rotation could be detected, just as a fly on the spoke of a rapidly rotating wheel could not tell from observing other flies on the hub or rim whether the wheel was stationary or spinning. Fortunately, however, we have good reason to believe that instead of uniform distribution, the stars are more condensed towards the centre of the system. The conditions of rotation will then approximate those in the solar system where most of the matter is at the centre and where the inner planets rotate more rapidly, both linearly and angularly, than the outer. If the galaxy rotates in this manner, there will obviously be relative motion

between the sun and neighboring stars which can be measured by the spectroscope and the circumstances of the rotation determined.

Oort developed the simple relation that exists between the radial velocities of neighboring stars and showed that the rotational effect is directly proportional to the distance from the sun and varies as we go around the galaxy, with the sine of twice the angle between the star and the direction of the gravitational centre. This centre is

ROTATION OF THE GALAXY



Absolute motions due to rotation
(Galactic Plane)

Star	l	Motions
S_5	10°	max.+ve
S_6	100°	max.-ve
S_7	190°	max.+ve
S_8	280°	max.-ve

generally assumed as in galactic longitude 327° and as coinciding with the centre of the system of globular clusters. The rotational effect $\bar{r}A$ is composed of the constant dynamical term A of an average value as determined by Oort and Plaskett of 1 km. per sec. for stars 60 parsecs, 200 light years from the sun. This value of A obviously provides a new method of obtaining the average distance $\bar{r}$ of a group of stars from the sun when $\bar{r}A$ has been obtained and also gives

accurate relative distances, independent of the value of A, of groups of stars or interstellar matter. I should like you to remember this deduction of the galactic rotation as it has an important application later. The diagram shows graphically how the rotational swing of the velocities has a double wave effect as one goes around the galaxy.

The radial velocities of the interstellar matter in the directions of some 260 stars were first analysed for the solar motion and the galactic rotation simultaneously by the method of least squares which is nothing more than a mathematical device for obtaining the most probable values of these unknown quantities from all the data. The results of this analysis and the equations used are shown in Table I

TABLE I.—SOLUTIONS OF INTERSTELLAR MOTIONS.

$$\bar{V} = X \cos L \cos B + Y \sin L \cos B + Z \sin B + \bar{r}A \sin 2(\bar{l} - l_0) \cos^2 \bar{b} + K$$

where

$\bar{V}$ = Average Radial Velocity of Group of Stars
X, Y, Z = Three Components of Solar Velocity
L = Galactic Longitude Solar Apex
B = Galactic Latitude Solar Apex
$\bar{r}$ = Average Distance of Group of Stars
A = Radial Rotational Term
$\bar{l}$ = Galactic Longitude of Group of Stars
$\bar{b}$ = Galactic Latitude of Group of Stars
lo = Galactic Longitude of Centre of Rotation
K = Average Residual Velocity

	1. General Solution	2. Particular Solution	
$V =$	$+ 19.90 \pm 2.40$ km. per second	$+ 20.00$	Assumed
$L =$	$25^\circ.9 \pm 11^\circ.8$	$21^\circ.8$	Assumed
$B =$	$+ 3^\circ.6 \pm 11^\circ.8$	$+ 20^\circ.0$	Assumed
$\bar{r}A =$	$+ 7.30 \pm 1.98$	$+ 7.90 \pm 0.79$	
$K =$	$+ 0.55 \pm 2.70$	$- 0.61 \pm 0.57$	
$=$	$335^\circ.1 \pm 15^\circ.5$	$331^\circ.7 \pm 5^\circ.7$	

and it is at once seen that the solar velocity agrees exactly with that obtained from the naked eye stars, of 20 km. per sec. This is interesting and important as indicating the normal motion of the interstellar matter. The position of the solar apex is however, about 20° distant from the normal position, not surprising in view of the unsuitable distribution so closely confined to the galactic plane. The rotational term of + 7.3 km. corresponds to an average distance of the centres of absorption of the diffuse matter of about 1450 light

years. A second solution was made for galactic rotation only, first removing the component of the standard solar motion. The results are much more accurate and give an average distance of nearly 1600 light years and a direction to the centre of 331°.7 ± 5°.7 agreeing with the accepted position well within the probable errors of the determination. I think all will agree when the observed and computed velocities, $\bar{v}$ and v' for the first or general solution and $\bar{\rho}$ and ρ' for the second solution for galactic rotation only, Table II, are compared

TABLE II.—Comparison of Observed and Computed Velocities.

				1. General Solution			2. Particular Solution		
No.	*	$\bar{l}$	$\bar{b}$	$\bar{v}$	v'	$\bar{v} - v'$	$\bar{\rho}$	ρ'	$\bar{\rho} - \rho'$
1	4	346°	+22°	−12.7	−11.7	− 1.0	+ 3.4	+2.6	+ 0.8
2	4	353	− 7	−12.2	−11.7	− 0.5	+ 3.9	+4.6	− 0.7
3	15	19	+ 5	−13.4	−12.0	− 1.4	+ 5.8	+7.2	− 1.4
4	8	32	+ 5	−13.1	−12.6	− 0.5	+ 5.7	+6.2	− 0.5
5	4	38	−32	− 6.4	−11.0	+ 4.6	+ 5.0	−3.5	+ 1.5
6	32	41	+ 1	−13.6	−13.2	− 0.4	+ 4.2	+4.5	− 0.3
7	20	52	+ 1	−10.8	−14.1	+ 3.3	+ 5.0	+2.1	+ 2.9
8	33	71	+ 6	−15.0	−15.0	− 0.0	− 2.3	−3.1	+ 0.8
9	17	67	−13	−14.5	−14.2	− 0.3	− 3.2	−1.9	− 1.3
10	18	86	− 5	−14.4	−14.0	− 0.4	− 6.9	−6.4	− 0.5
11	7	96	− 3	−14.8	−12.6	− 2.2	−10.5	−7.9	− 2.6
12	11	104	− 1	−21.4	−10.6	−10.8	−18.9	−8.5	−10.4
13	15	116	+ 2	− 3.5	− 6.8	+ 3.3	− 4.4	−8.1	+ 3.7
14	13	132	− 5	+ 8.5	+ 0.8	+ 7.7	+ 1.0	−5.7	+ 6.7
15	14	156	− 2	+12.0	+12.4	− 0.4	− 0.5	−0.1	− 0.4
16	16	172	+ 3	+19.0	+20.9	− 1.9	+ 3.2	+4.5	− 1.3
17	24	173	−17	+19.3	+20.3	− 1.0	+ 2.2	+4.5	− 2.0
18	4	194	0	+31.3	+27.1	+ 4.2	+12.8	+7.2	+ 5.6
19	2	218	+54	+13.4	+12.4	+ 1.0	+ 8.4	+1.4	+ 7.0

that this diffuse matter follows remarkably closely the double wave swing of the velocities produced by a rotation of the galaxy. The early assumption that this interstellar matter is relatively at rest was evidently erroneous as the residual velocities $\bar{\rho}$ are of considerable magnitude and are practically removed by the rotational effect, as the residuals remaining, $\bar{\rho} - \rho'$, are negligible except in two or three positions which time does not permit us to discuss. There can be no reasonable doubt that this interstellar diffuse matter, indeed almost

its individual molecules, partakes almost exactly of the orderly differential rotation of the galactic system.

This demonstration of the rotational motions of the interstellar matter leaves only the question of its distribution unsettled. This follows directly from the proportionality of the average distance of a group of stars or clouds to the rotational term $\bar{r}A$. As mentioned above there are available about 230 high temperature stars for which we have the radial velocities not only of the stars themselves but also of the intervening diffuse matter. The estimation of the intensity of "interstellar" H and K in these stars gives, as was indicated above, a means of arranging them in groups according to distance. A second method of grouping in distance which, however, owing to the dispersion in the intrinsic brightness of the stars is not so critical, is by arranging them in groups in apparent magnitude. The arrangement by both methods is shown in Table III with the values of the rotational term,

TABLE III.—SOLUTIONS OF MAGNITUDE GROUP.

Group	No.	m	rA Stars	rA Clouds
1	37	4.41	+ 1.81±2.8	+ 3.85±1.2
2	45	5.60	+10.26±2.1	+ 5.02±1.2
3	79	6.03	+13.86±1.8	+ 7.66±0.9
4	119	7.00	+16.58±2.2	+ 8.31±1.4
5	69	7.34	+20.49±2.3	+10.08±1.6

SOLUTIONS OF INTENSITY GROUPS.

Group	No.	I	rA Stars	rA Clouds
1	42	4.72	+ 3.64±3.2	+ 4.97±0.8
2	662	6.50	+12.12±1.9	+ 4.93±0.9
3	90	6.08	+10.22±1.7	+ 5.03±0.8
4	79	7.46	+14.53±2.9	+ 6.91±1.1
5	43	8.42	+27.52±2.5	+13.72±1.2

$\bar{r}A$, for both stars and intervening matter for each group. Except for the brighter and nearer stars, where the rotational term is indeterminate, the remarkable relation holds almost exactly that $\bar{r}A$ for the stars is just twice that for the corresponding intervening diffuse matter, in other words that the average distance of each group of stars is just twice that of the centre of gravity of the intervening clouds. When this holds for the seven more distant groups at average distances from the sun of 2,000, 3,000, 4,000 and 5,500 light years

TABLE IV.—Comparison of Velocities.

Group	No.	Mean Long.	Stellar Velocities		Cloud Velocities	
			Observed	Computed	Observed	Computed
Intensity of Interstellar Lines 4.4 to 6.9			$rA = +10.22$		$rA = +5.03$	
1	2	345°	+36.2	+10.8	−1.2	+3.3
2	2	17	+ 5.9	+14.0	+4.9	+4.9
3	14	38	+10.4	+ 9.9	+5.7	+2.9
4	11	61	+ 6.4	+ 2.1	−0.4	−1.0
5	13	75	− 7.3	− 2.4	−0.4	−3.2
6	8	89	− 6.8	− 5.3	−6.0	−4.6
7	8	113	− 2.1	− 5.0	−6.9	−4.4
8	6	131	+ 4.5	− 0.5	+2.7	−2.2
9	8	156	+ 7.0	+ 8.0	−1.7	+2.0
10	13	174	+14.4	+12.6	+4.9	+4.1
11	3	205	− 2.6	+ 9.8	+3.4	+4.2
Intensity of Interstellar Lines 7.0 to 7.9			$rA = +14.53$		$rA = +6.91$	
1	8	12	+ 5.5	+14.3	+ 4.6	+ 6.7
2	12	38	+ 8.9	+ 8.0	+ 6.3	+ 3.7
3	11	51	+ 7.2	+ 1.7	+ 4.8	+ 0.6
4	10	65	− 1.5	− 5.3	− 0.9	− 2.6
5	4	75	− 7.8	− 9.5	− 2.4	− 4.7
6	8	89	−20.2	−13.7	−10.6	−16.7
7	3	110	−23.9	−13.9	− 9.7	− 6.7
8	3	139	+ 1.7	− 3.2	− 0.3	− 1.7
9	9	160	+10.6	+ 7.2	+ 0.2	+ 3.3
10	10	174	+17.2	+12.2	+ 2.7	+ 5.6
11	1	192	+44.6	+14.4	+13.0	+ 6.7
Intensity of Interstellar Lines 8.0 to 9.5			$rA = +27.52$		$rA = +13.72$	
1	2	358	+35.7	+24.3	+ 8.2	+ 9.4
2	2	17	+12.2	+29.3	+ 6.1	+11.9
3	6	34	+21.5	+21.3	+ 7.5	+ 7.9
4	2	47	+11.8	+10.4	+ 6.6	+ 2.4
5	12	70	− 3.4	−10.4	− 5.4	− 8.0
6	4	97	−26.8	−23.4	−15.5	−14.3
7	9	107	−28.4	−23.5	−17.7	−14.5
8	4	141	− 4.1	− 0.9	+ 1.2	− 3.2
9	2	169	+13.6	+16.0	+ 1.9	+ 5.3

and intermediate distances there can be no escape from the conclusion that this very diffuse interstellar matter is uniformly distributed throughout the space inhabited by the *O* and *B* type stars, to distances of at least 5,500 light years from the sun. It will be worth while to show a comparison of observed and computed residual velocities, Table IV, to give further ocular demonstration of the unmistakable reality of the galactic rotation.

The conclusions in regard to the presence, properties and motions of diffuse matter in interstellar space may be profitably summarized in three stages:—

1. The early investigation of the radial velocities of the *O* type stars at Victoria conclusively showed the fairly extensive distribution of diffuse interstellar matter which at first appeared to be nearly at rest in the stellar system and through which the high temperature stars were rapidly moving in all directions.

2. Eddington, on the basis of this observational data, developed a beautiful theory of the physical properties of this diffuse matter whose density, temperature and the conditions for the selective absorption of the star light were calculated. These calculations entailed the assumption of uniform distribution of the interstellar material.

3. Just as the early observations at Victoria furnished the foundation on which Eddington built his masterly theoretical super-structure, so our more recent investigation may rightly claim to have placed the final observational capstone on the whole structure. It seems to me it has added immeasurably to our conviction of the objective reality of this exceedingly diffuse interstellar matter to have proved that it partakes in the most beautifully exact way of the differential motions produced by a rotation of the galaxy and to have demonstrated conclusively from these motions that it is uniformly distributed throughout the stellar system.

The history of the manner in which the presence and properties of diffuse matter in interstellar space were discovered, calculated and demonstrated forms a striking illustration of the fruitful combination of theory and practice.